

Investigation of Anode-side Temperature Effect in 1200V FWD Cosmic Ray Failure

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Abstract— This paper presents a new cosmic ray failure mechanism of FWDs based on TCAD, and proposes novel FWDs with higher withstanding capability against cosmic rays, which induce device failure. The novel FWDs have a very thin additional P⁺ layers on the surface of the anode layer to prevent catastrophic temperature rise due to high energy ion irradiation. The high energy Si ions, which are generated by the neutron irradiation, induce high temperature rise in the anode surface. TCAD analysis shows that if the anode surface temperature becomes so high, large minority carrier generation in the surface causes electron current injection from the P⁺ surface, resulting in high temperature increase and the resultant silicon melting inside FWDs. In the novel FWDs, the temperature rise is suppressed by the additional P⁺ layer. Experimental verification was also executed to confirm the successful suppression of the device failure by neutron irradiation.

Keywords—FWDs; TCAD; Simulation; Cosmic-ray; Neutron irradiation; Failure rate

I. INTRODUCTION

Most of the errors of high voltage semiconductor devices such as power-MOSFETs, IGBTs and FWDs, induced by cosmic rays at terrestrial environment are well known as Single-Event-Burn-out(SEB), which causes the shut-down of total systems, for example, UPS and PCS (power conditioning system). In order to decrease the probability of this fatal failure in the system it is necessary to have the capability to withstand neutron irradiation which makes heavy ions by the nuclear reaction with Si atoms.

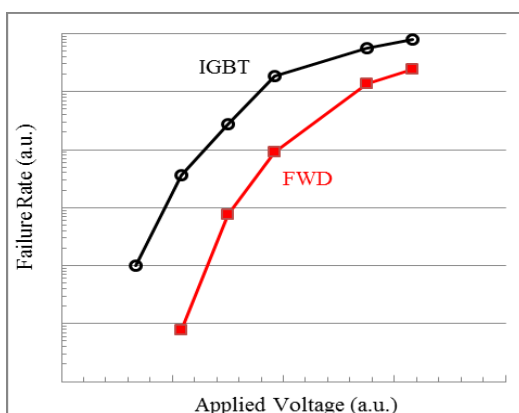


Fig. 1. Measured failure rate of IGBTs and FWDs as a function of applied DC voltage.

Figure 1 presents the dependence of the failure rates of 1200V rated IGBTs and FWDs on applied DC voltage. Higher failure rate was observed for higher DC voltage, although the failure rate of FWDs was lower than that of IGBTs. It is now well known that neutrons, induced by cosmic rays, strike MOSFETs or IGBTs, and triggers parasitic bipolar and/or thyristor action[1,2]. In the case of FWDs cosmic failures were mainly discussed with proton or heavy ion irradiation[3-5]. However, improvement methods of FWDs for neutron irradiation have not been clarified yet, so far. The purpose of this paper is to investigate the failure mechanism by TCAD and to improve device design of FWDs.

II. TCAD ANALYSIS

A. TCAD 3D-calculation Model

Figure 2 shows a cross-section of FWD 3D cylindrical model. We assume that neutrons collide with Si atoms, and high energy Si ions are generated. Figure 3 shows the energy (LET_f) distribution of a Si ion which has energy of 200 MeV. Si ion is assumed to be generated at the anode surface in the central axis of the 3D model. By the incidence of a Si ion, electron-hole pairs are generated along the central axis of the 3D model, as shown in Fig.4. DC reverse bias voltage is also applied through the calculation.

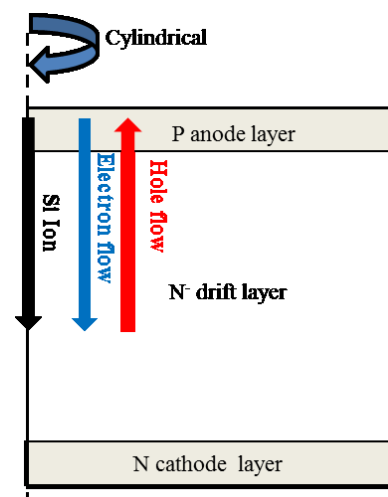


Fig. 2. Cross-section of simulated model (3D cylindrical model) of FWD. Electrons are injected from the P layer surface in the case of failure.

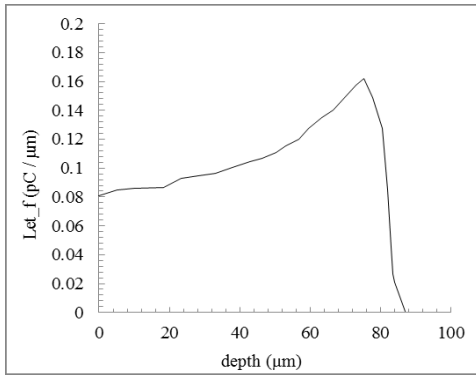


Fig. 3. 200MeV Si ion linear energy transfer distribution used in simulations (Let_f vs. depth).

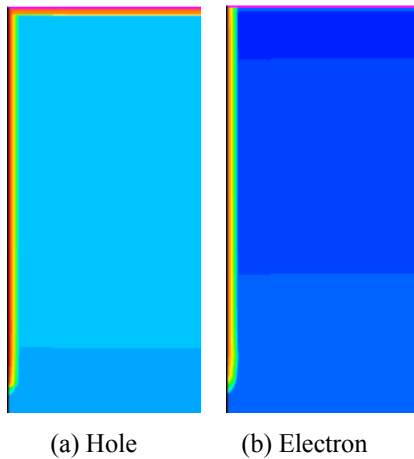
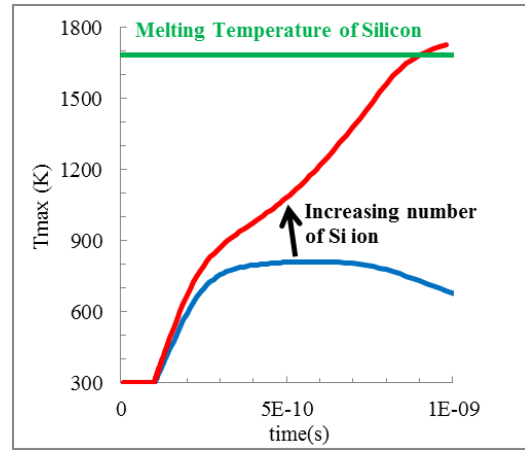


Fig. 4. Simulated hole and electron distribution which is generated by the incidence of Si ion: (a)Hole (b)Electron. Holes and electrons are generated along the Si ion trail (along the central axis).

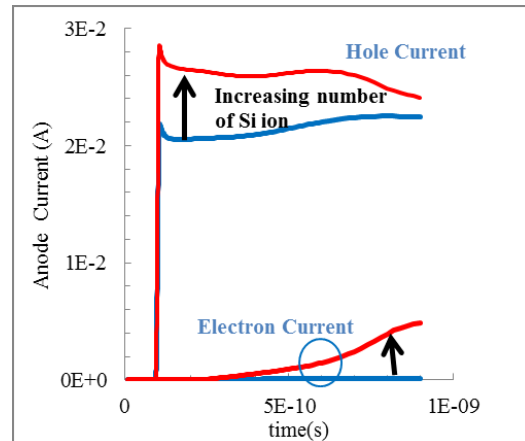
B. SEB Mechanism of FWDs

Figures 5 show the simulated waveforms of the maximum temperature in the anode layer (a) as well as the waveforms of the anode hole/electron currents (b), when the number of the incident Si ions is changed, in other words, the LET_f is multiplied by the number of Si ions. When the number of Si ions is a few, small temperature rise is observed, and just hole current flows through the anode layer. On the other hand, when the number of Si ions becomes large, the temperature of the anode layer surface is significantly increased and the surface region turns into intrinsic semiconductor. Sufficient minority carriers are generated in the surface, resulting in large electron current injection from the P⁺ layer surface. Both hole and electron currents flow through the anode layer. The maximum temperature inside the FWD reaches as high as the melting temperature of Silicon.

Figure 6 shows cross-sectional image of a broken point of FWD which was burned out in a neutron irradiation experiment. The sample is etched by focused ion beam. In this figure the surface electrode and Si are mixed. This result indicates that plenty of electric current passed through the anode layer and melted surface structure up during the burn-out process.



(a) Maximum temperature as a function of time.



(b) Anode hole and electron currents as a function of time.

Fig. 5. Simulated waveforms with varying number of Si ions: (a) Maximum temperature in the anode layer as a function of time, (b) Anode hole and electron currents as a function of time. The arrows in the figures show the change in the waveforms when the number of the Si ions are increased.

III. NOVEL FWDs (SIMULATION & EXPERIMENT)

A. Structure of novel FWDs and Simulation Result

Two novel FWDs are proposed and shown in Fig.7. The novel FWD1/FWD2 has an additional high impurity concentration P⁺ layer1/ P⁺ layer2 on the anode surface. The impurity concentration of the additional P⁺ layer2 is higher than that of the additional P⁺ layer1. The additional P⁺ layer suppresses the surface temperature rise effectively since higher temperature is required to turn the surface layer into intrinsic semiconductor. The simulated waveforms are compared between conventional FWDs and the two novel FWDs in Figs.8. The two novel FWD structures reduce the temperature rise and suppress the anode electron current injection, compared to conventional FWDs.

In the two novel FWDs, the required number of Si ions to cause melting of Silicon inside the FWDs is several or twenty times higher than that for conventional FWDs, as shown in Table.1.

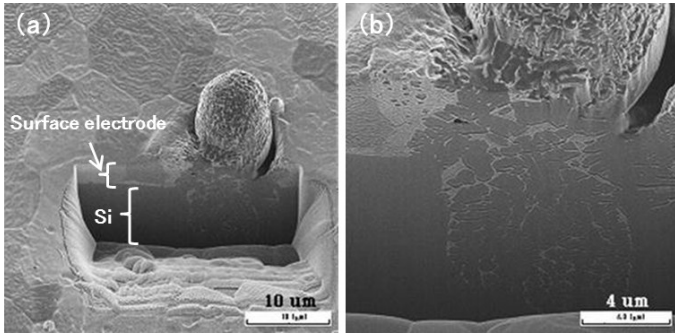


Fig. 6. Cross-sectional image of a broken point of FWD which was burned out in neutron irradiation experiment. (b) is high-resolution image of (a).

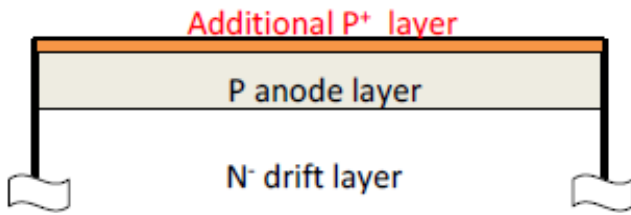


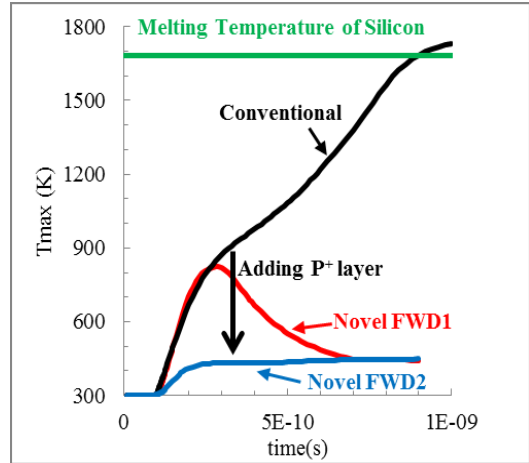
Fig. 7. Cross-section of novel FWDs structure to suppress the destruction by neutrons.

TABLE I. Comparison of the number of Si ion to cause device failure between conventional FWDs and novel FWDs. Impurity concentration of additional P+ layer2 is higher than that of additional P+ layer1.

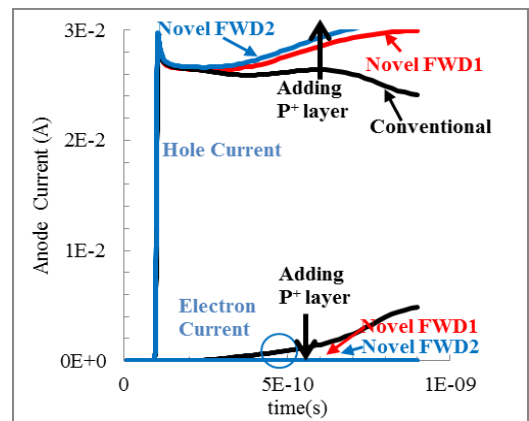
Structure type	Number of Si Ion
Conventional FWD	4.5
Novel FWD1 with additional P+ layer1	9
Novel FWD2 with additional P+ layer2	93

B. Experimental result of novel FWDs

According to the simulation result, we have fabricated the two novel FWDs and investigated the failure rate of them in an acceleration condition test by applying neutron beam. The energy spectrum of the neutron beam is adjusted to terrestrial condition. Figure 9 shows the measured failure rate of the two novel FWDs and conventional FWD as a function of applied DC voltage. Thanks to the TCAD simulation prediction, the failure rate of the two novel FWDs was successfully reduced, compared with that of the conventional FWD.



(a) Maximum temperature as a function of time.



(b) Anode hole and electron currents as a function of time.

Fig. 8. Simulated waveforms of two novel FWDs: novel FWD1 with additional P+ layer1 and novel FWD2 with additional P+ layer2. Impurity concentration of additional P+ layer2 is higher than that of additional P+ layer1 (a) Maximum temperature of anode layer, (b) Anode hole and electron currents.

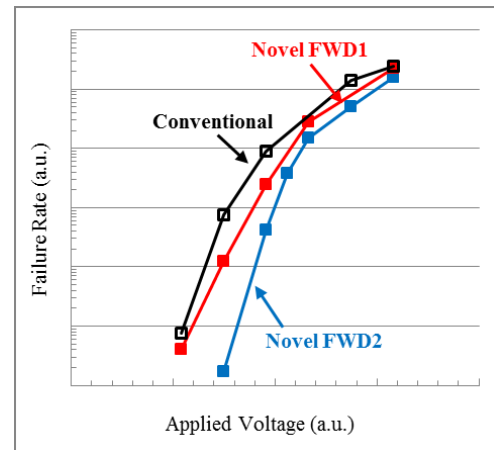


Fig. 9. Comparison of measured failure rate between conventional FWDs and novel FWDs.

IV. CONCLUSION

A new cosmic ray failure mechanism of FWDs and new novel FWD structures are presented in this paper based on TCAD. Proposed novel FWDs which have thin additional P⁺ layers have very good cosmic ray hardness. Furthermore, we have successfully demonstrated high cosmic ray reliability of novel FWDs experimentally.

In this study we have invented the desirable FWD structure for cosmic ray irradiation. As a next step, it is necessary to make efforts to find out strong edge termination structures of FWDs for the applications.

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